AFRL-AFOSR-UK-TR-2012-0055

Solar Flares at High Spatial and Temporal Resolution

Professor Mihalis Mathioudakis

Queen's University Belfast
School of Mathematics and Physics
University Road
Belfast BT7 1NN United Kingdom

EOARD Grant 09-3085

Report Date: November 2012

Final Report for 20 July 2009 to 19 July 2012

Air Force Research Laboratory
Air Force Office of Scientific Research
European Office of Aerospace Research and Development
Unit 4515 Box 14, APO AE 09421

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From – To)*
28 November 2012	Final Report	20 July 2009 – 19 July 2012

4. TITLE AND SUBTITLE

Solar Flares at High Spatial and Temporal Resolution

5a. CONTRACT NUMBER

FA8655-09-1-3085

5b. GRANT NUMBER

Grant 09-3085

5c. PROGRAM ELEMENT NUMBER

61102F

6. AUTHOR(S)

Professor Mihalis Mathioudakis

5d. PROJECT NUMBER

5d. TASK NUMBER

5e. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Queen's University Belfast
School of Mathematics and Physics
University Road
Belfast BT7 1NN United Kingdom

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
Unit 4515 BOX 14
APO AE 09421

10. SPONSOR/MONITOR'S ACRONYM(S)

AFRL/AFOSR/EOARD

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-AFOSR-UK-TR-2012-0055

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Solar flares vary in magnitude and duration from rare white-light flares to common microflares and other sub-arcsec resolution rapid energy releases. They represent the rapid transformation of the magnetic energy into thermal energy, particle acceleration and mass flows. Flares are phenomena which manifest themselves over a broad range of the electromagnetic spectrum. Although they are often viewed as high-energy processes which occur primarily in the corona, the response of the photosphere and chromosphere to the flare energy transport is very complex, and the energy radiated from the lower atmosphere forms an important part of the energy budget. It is therefore essential that the photospheric and chromospheric signatures and processes involved are well understood. A detailed investigation of flare phenomena at high spatial and temporal resolutions was carried out, primarily employing the new solar imager, ROSA (Rapid Oscillations in the Solar Atmosphere). ROSA is a 6-CCD system capable of observing the Sun simultaneously in multiple wavebands at a cadence of up to 200 Hz (30 Hz for the full 1K 1K chip). ROSA is being developed as a common-user instrument, and is available on the Dunn Solar Telescope (DST) at the National Solar Observatory (NSO) Sacramento Peak. It provides high cadence, high spatial resolution observations of the solar atmosphere, and allows the investigation of solar oscillatory phenomena and impulsive events at an unprecedented level of detail. The report includes summaries of research outputs covered by this grant. It focuses on results that have been published or have been submitted for publication to refereed journals. Where the work has been published or accepted for publication the relevant reference is listed.

15. SUBJECT TERMS

EOARD, solar flares, solar atmosphere, ROSA, space weather, solar monitoring, solar physics

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18, NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Thomas Caudill
UNCLAS	UNCLAS	UNCLAS	SAR	14	19b. TELEPHONE NUMBER *(Include area code)* +44 (0)1895 616086

Final Report on Grant FA8655-09-13085

Solar Flares at High Spatial and Temporal Resolution

PI : Mihalis Mathioudakis, School of Mathematics and Physics, Queen's University Belfast

The report includes summaries of research outputs covered by this grant. It focuses on results that they have published or have been submitted for publication to refereed journals. Where the work has been published or accepted for publication we list the relevant reference. Due to the large file sizes we do not attach the manuscripts. However, the manuscripts are available and can be provided on request. Two of the publications include contributions from AFRL personnel.

Micro-flare Activity Driven by Forced Magnetic Reconnection

Authors : D.B. Jess, M. Mathioudakis, P.J. Crockett , F.P. Keenan (QUB), P.K Browning (University of Manchester)

Summary : High cadence, multiwavelength, optical observations obtained with the Swedish Solar Telescope, are presented. Two magnetic bright points are seen to separate in opposite directions at a constant velocity of 2.8 km s^{-1}. After a separation distance of 4,400 km, multiple Ellerman bombs are observed in both Hα and Ca II K images. Periodic velocity perturbations in the vicinity of the magnetic neutral line, derived from the Michelson Doppler Imager, are generated with an amplitude of 6 km s^{-1} and wavelength of 1,000 km. The velocity oscillations are followed by an impulsive brightening visible in Hα and Ca II K , with a peak intensity enhancement of 63%. These velocity perturbations are interpreted as the magnetic field deformation necessary to trigger forced reconnection. A time delay of 3 minutes between the Hα wing and Ca II K observations indicated that the observed magnetic reconnection occurs at a height of 200 km above the solar surface. These observations are consistent with theoretical predictions and provide the first observational evidence of microflare activity driven by forced magnetic reconnection.

This work has been published in the Astrophysical Journal Vol 712, L111 (2010)

Small-scale Hα Jets in the Solar Chromosphere

Authors : D.Kuridze, M. Mathioudakis, D.B. Jess, S. Shelyag, F.P. Keenan (QUB),
D.J. Christian (Cal State Northridge),
K.S. Balasubramaniam (AFRL,Sunspot)

Summary : The solar chromosphere is permeated by a wide of highly dynamic features including jets, fibrils, mottles, spicules, Ellerman bombs and Hα surges. In particular, chromospheric jets are one of the most important, yet also most poorly understood phenomena of the Sun's magnetic atmosphere. The energy required to drive these chromospheric jets can be released by magnetic reconnection occurring in the lower solar atmosphere. We use high resolution observations obtained with the Dunn Solar Telescope equipped with the Rapid Oscillations in the Solar Atmosphere instrument to study the velocities of small scale jets in an emerging solar active region. Our dataset comprises of Hα, Ca II K and G-band imaging together with line-of-sight photospheric magnetograms. The Hα images are highly dynamic with estimated jet velocities as high as 45 km s^{-1}. The jets are one directional and their origin is linked to underlying Ca II K brightenings and G-band bright points. We suggest that a siphon flow model of cool coronal loops is appropriate for the interpretation of the observations. The jets are associated with small scale explosive events and may provide a mass outflow from the photosphere to the corona.

This work has been published in Astronomy and Astrophysics Vol 533, A76, (2011)

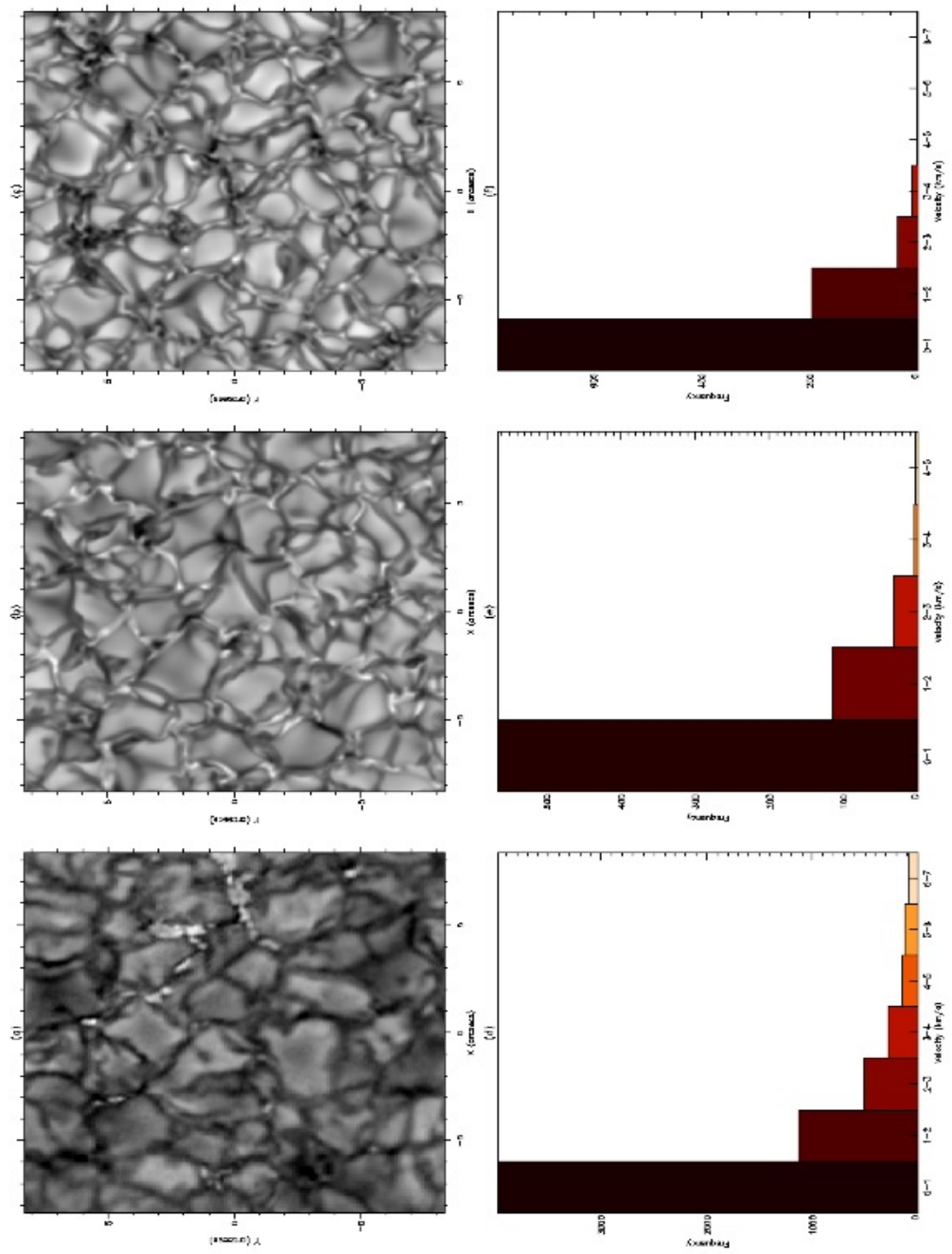
The Velocity Distribution of Solar Photospheric Magnetic Bright Points

Authors : P.H. Keys M. Mathioudakis, D.B. Jess, S. Shelyag, F.P. Keenan (QUB), D.J. Christian (Cal State Northridge),

Summary : Solar photospheric Magnetic Bright Points (MBP) play a crucial role in the structure and dynamics of the lower solar photosphere. These are some of the smallest resolvable features on the solar surface having diameters as low as 100 km (at the diffraction limit of current instrumentation). The merging of MBPs can lead to small scale reconnection events and flares while their transverse velocities can excite magneto-acoustic waves that are used as a conduit to transporting energy in the corona. We use high resolution observations and numerical simulations to study the velocity distribution of MBPs. The observations were obtained with the Dunn Solar Telescope equipped with the Rapid Oscillations in the Solar Atmosphere instrument. The numerical simulations were carried out with the MURaM radiative Magneto-hydrodynamic code. We implement an automated MBP detection and tracking algorithm on the dataset and study the velocity characteristics of over 6,000 structures. We find average velocities of approximately 1 km s^{-1} and maximum velocities as high as 7 km s^{-1}. Merging MBPs were found to have significantly higher velocities and longer lifetimes than isolated structures. We implement a new novel technique and estimate that our observational data can be best described with an average magnetic field strength of 400 G.

This work has been published in the Astrophysical Journal Vol . 740, L40, (2011)

The Velocity Distribution of Solar Photospheric Magnetic Bright Points



Caption : Panels on the left contain snapshots of the solar photosphere from (a) observations, (b) 200 G radiative MHD simulations and (c) 400 G radiative MHD simulations. The corresponding velocity distributions are shown on the right (panels d-f). The snapshots on the left have dimensions of 11,600 km x 11,600 km.

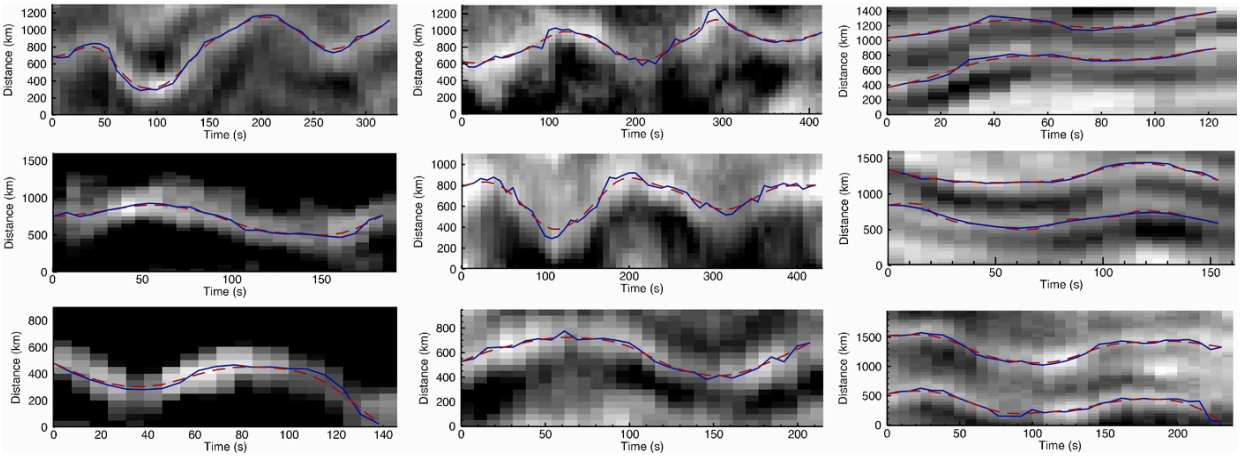
Transverse Oscillations in Chromospheric Mottles

Authors : D. Kuridze (QUB), R.J. Morton, R. Erdelyi (Sheffield), G.D. Dorrian, M. Mathioudakis, D.B. Jess, F.P. Keenan (QUB)

Summary : A number of recent investigations have revealed that transverse waves are ubiquitous in the solar chromosphere. The vast majority of these have been reported in limb spicules and active region fibrils. We investigate long-lived, quiet-Sun, on-disk features such as chromospheric mottles (jet-like features located at the boundaries of supergranular cells) and their transverse motions. The observations were obtained with the Rapid Oscillations in the Solar Atmosphere instrument at the Dunn Solar Telescope. The data set is comprised of simultaneous imaging in the Hα core, Ca II K, and *G* band of an on-disk quiet-Sun region. Time–distance techniques are used to study the characteristics of the transverse oscillations. We detect over 40 transverse oscillations in both bright and dark mottles, with periods ranging from 70 to 280 s, with the most frequent occurrence at ~165 s. The velocity amplitudes and transverse displacements exhibit characteristics similar to limb spicules. Neighboring mottles oscillating in-phase are also observed. The transverse oscillations of individual mottles are interpreted in terms of magnetohydrodynamic kink waves. Their estimated periods and damping times are consistent with phase mixing and resonant mode conversion.

This work has been published in the Astrophysical Journal Vol 750, 51 (2012).

Transverse Oscillations in Chromospheric Mottles



Caption : Time-distance diagrams of the mottle intensity in Hα. The blue line is the centroid of a Gaussian fit to the cross-sectional flux profile of the mottle at each time step smoothed by a ~50 km width (red line).

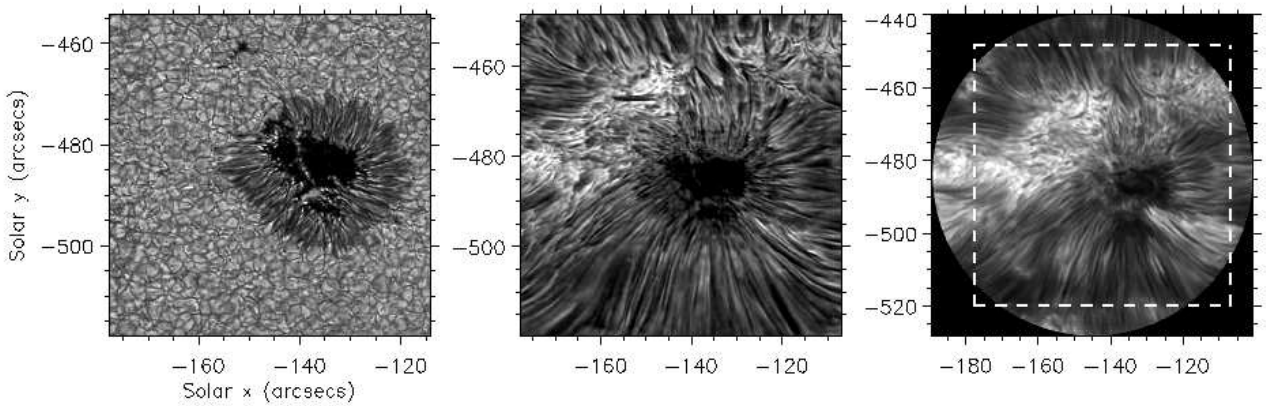
The Source of Three-minute Magneto-acoustic Oscillations in Coronal Fans

Authors : D. B. Jess (QUB), I. De Moortel (St Andrews), M. Mathioudakis (QUB), D. J. Christian (Cal State, Northridge), K. P. Reardon, P. H. Keys, F. P. Keenan (QUB)

Summary : We use images of high spatial, spectral and temporal resolution, obtained using both ground- and space-based instrumentation, to investigate the coupling between wave phenomena observed at numerous heights in the solar atmosphere. Analysis of 4170 A˚ continuum images reveals small-scale umbral intensity enhancements, with diameters ∼0 .6", lasting in excess of 30 minutes. Intensity oscillations of ≈3 minutes are observed to encompass these photospheric structures, with power at least three orders-of-magnitude higher than the surrounding umbra. Simultaneous chromospheric velocity and intensity time series reveal an 87 ± 8◦ out-of-phase behavior, implying the presence of standing modes created as a result of partial wave reflection at the transition region boundary. We find a maximum wave guide inclination angle of ≈40◦ between photospheric and chromospheric heights, combined with a radial expansion factor of <76%. An average blue-shifted Doppler velocity of ≈1.5 km per sec, in addition to a time lag between photospheric and chromospheric oscillatory phenomena, confirms the presence of upwardly-propagating slow-mode waves in the lower solar atmosphere. Propagating oscillations in EUV intensity are detected in simultaneous coronal fan structures, with a periodicity of 172 ± 17 s and a propagation velocity of 45 ± 7 km s−1 . Numerical simulations reveal that the damping of the magneto-acoustic wave trains is dominated by thermal conduction. The coronal fans are seen to anchor into the photosphere in locations where large-amplitude umbral dot oscillations manifest. Derived kinetic temperature and emission measure time-series display prominent out-of-phase characteristics, and when combined with the previously established sub-sonic wave speeds, we conclude that the observed EUV waves are the coronal counterparts of the upwardly-propagating magneto-acoustic slow-modes detected in the lower solar atmosphere. Thus, for the first time, we reveal how the propagation of 3 minute magneto-acoustic waves in solar coronal structures is a direct result of amplitude enhancements occurring in photospheric umbral dots.

This work has been published in the Astrophysical Journal Vol 757, 160, (2012).

The Source of Three-minute Magneto-acoustic Oscillations in Coronal Fans



Caption : Simultaneous images of the lower solar atmosphere, obtained through 4170 A continuum (left), Hα core (middle), and Ca II 8542 A core (right) filters at 13:32 UT on 2011 July 13. The Ca II 8542 A image displays Doppler-compensated intensities, while the dashed white box outlines the ROSA/HARDcam field-of-view. Axes are in heliocentric arcseconds, where $1'' \approx 725$ km on the solar surface.

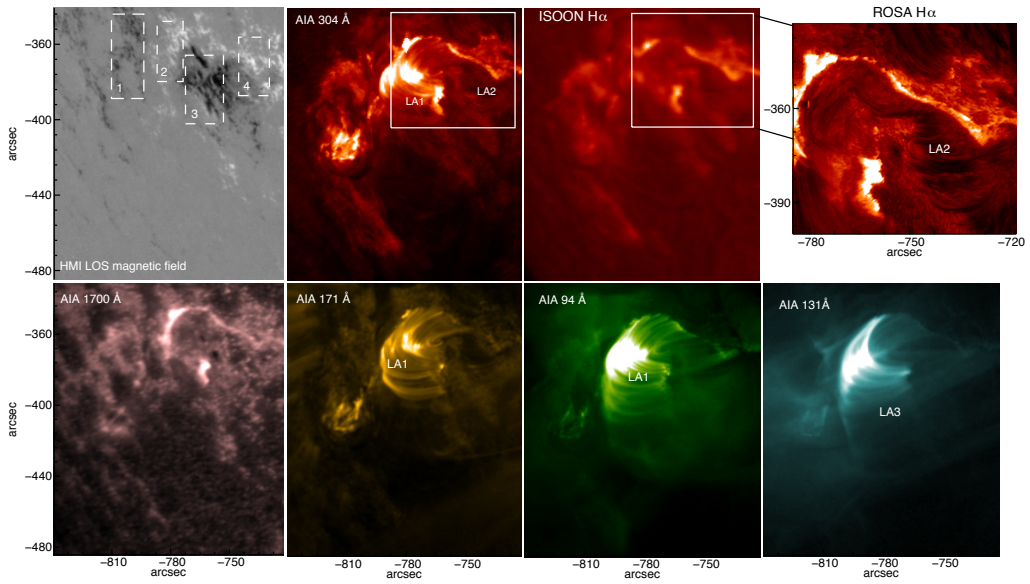
A failed filament eruption inside a coronal mass ejection in active region 11121

Authors : D. Kuridze, M. Mathioudakis (QUB), A.F. Kowalski (UoW Seattle), P.H. Keys, D.B. Jess (QUB), K.S. Balasubramaniam (AFRL), F.P. Keenan (QUB)

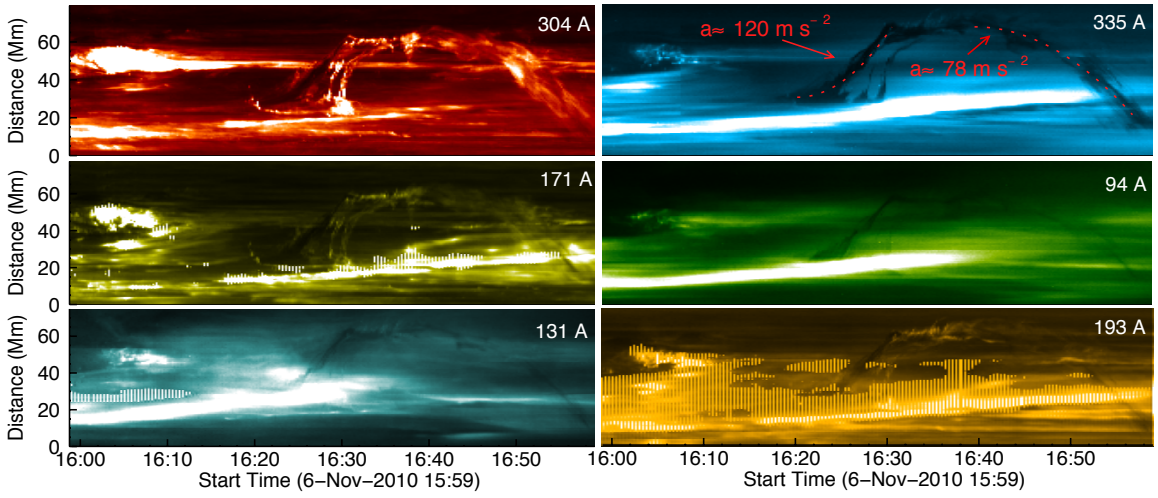
Summary : We study the formation and evolution of a failed filament eruption observed in NOAA active region 11121 near the southeast limb on November 6, 2010. We use a time series of SDO/AIA 304, 171, 131, 193, 335, 94 A images, SDO/HMI magnetograms, plus ROSA and ISOON Hα images, to study the erupting active region. We identify coronal loop arcades associated with a quadrupolar magnetic configuration, and show that the expansion and cancelation of the central loop arcade system over the chromospheric filament is followed by the eruption of the filament. The erupting filament reveals a clear helical twist and develops a same sign of writhe in the form of inverse γ-shape. The observations support the "magnetic breakout" process with the eruption been triggered by quadrupolar reconnection in the corona. We suggest that the formation mechanism of the inverse γ-shape flux rope may be the MHD helical kink instability.

This work is under review in Astronomy and Astrophysics.

The Failed Filament Eruption of Active Region 11121



Caption : Simultaneous SDO/AIA, ROSA, ISOON images and SDO/HMI magnetograms of the erupting region. Four white, dashed boxes in the HMI line-of-sight (LOS) magnetogram denote basic patches of positive and negative magnetic flux concentrations. The large white boxes in the AIA 304 A and ISOON images indicate the ROSA Hα field-of-view. The AIA 1700 A image shows the position of the main flare ribbon. LA1, LA2 and LA3 are three different loop arcade systems. LA2 consist of very small chromospheric loops which are not resolved in the AIA and ISOON Hα images, but are detected in the high spatial resolution ROSA Hα images.



Caption : Time-distance diagrams that show the simultaneous upward motions of the eruption and downward streams in different SDO/AIA bandpasses.

Observations of ubiquitous compressive waves in the Sun's chromosphere

Authors : R. J. Morton (Sheffield), G. Verth (Sheffield), D. B. Jess (QUB), D. Kuridze (QUB), M. S. Ruderman (Sheffield), M. Mathioudakis (QUB) & R. Erdélyi (Sheffield)

Summary: The details of the mechanism(s) responsible for the observed heating and dynamics of the solar atmosphere still remains a mystery. Magnetohydrodynamic (MHD) waves are thought to play a vital role in this process. Although it has been shown that incompressible waves are ubiquitous in off-limb solar atmospheric observations their energy cannot be readily dissipated. We provide here, for the first time, on-disk observation and identification of concurrent MHD wave modes, both compressible and incompressible, in the solar chromosphere. The observed ubiquity and estimated energy flux associated with the detected MHD waves suggest the chromosphere is a vast reservoir of wave energy with the potential to meet chromospheric and coronal heating requirements. We are also able to propose an upper bound on the flux of the observed wave energy that is able to reach the corona based on observational constraints, which has important implications for the suggested mechanism(s) for quiescent coronal heating.

This work has been accepted for publication in Nature Communications.